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# 5

# Non-Invasive Coronary Angiography

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## 1. Introduction

Computed Tomography (CT) scanners essentially consist of a rotating X-ray tube emitting a fan-beam of X-rays mounted on a gantry opposite a set of curvilinear detector rows. The X-ray beam, collimated at source and prior to detection, rotates around the patient who lies on a table that passes through the gantry. The gantry may either move sequentially down the table (step and shoot) or the table and the gantry move together (helical scanning) thereby reducing scan times and improving temporal resolution.

Early CT scanners, with only one detector and a pencil beam, took approximately 3 minutes to complete one 360$^{o}$ rotation around the patient. Fan shaped x-ray beams, increasing the number of detectors and the advent of slip-ring technology allow modern CT scanners to have speeds in excess of 330ms per rotation (with their absolute mechanical limit being between 50 and 200ms) and has allowed cardiac CT to flourish, and in particular allows motion free images of the coronary arteries to become a reality. (Kalender, 2000, as cited in Nicol & Padley, 2007a).

The detectors sense and record the attenuation of the X-ray beam for any given point in the imaged slice. In Cardiac CT (CCT) images are obtained with slice thicknesses as thin as 0.4mm. The X-ray attenuation is translated into a numerical value (Hounsfield Units (HU)). Multiple attenuation values are obtained from any given point during the rotation of the X-ray tube. Filtered back projection is then automatically performed to achieve a final attenuation value. These values are converted and mapped to form a grey-scale image.

Magnetic resonance uses a strong static magnetic field to effectively magnetise the protons in the body. Radiofrequency pulses are transmitted to excite the protons in the tissue being imaged and an echo signal is produced and recorded in the receiver coils and these are used to produce an image. Different types of pulse sequences can be used to take advantage of the different relaxation characteristics of the tissue to help generate image contrast. Typically a 1.5 tesla (T) MRI scanner is used for cardiac MR (CMR) and superior image quality is achieved by using higher numbers of receiver channels.

## 2. Technical aspects of CT and MR coronary angiography

CT and MR coronary angiography (CTCA and MRCA) depend on three main factors – spatial resolution, temporal resolution and contrast resolution.

### 2.1 Spatial resolution

Spatial resolution is defined as the ability to distinguish two separate objects in close proximity (Fig. 1) (Smith, 1997).

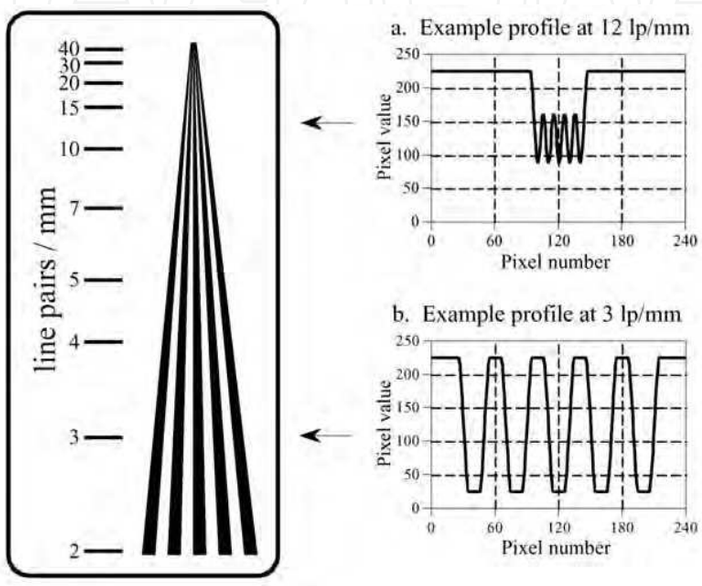



Fig. 1. Spatial resolution , expressed as line pairs/mm (lp/mm), is considered the point at which the individual strips cannot be readily distinguished by the eye. A line pair gauge such as this one is typically used to measure this. Reproduced with permission (Smith, 1997).

This is critically important in coronary artery imaging as coronary arteries have small luminal diameters, approximately 5mm at the ostia, tapering distally (or within the branches) to < 1mm. As CT and MR values for any given point is represented as a voxel (a three dimensional pixel), the smaller the voxel, the higher the spatial resolution. Other factors that affect spatial resolution may be fixed or variable. Fixed (non-modifiable) factors include scanner capabilities and patient size whilst variable factors include heart rate and motion artefact that can, to large extent, be mitigated.

#### 2.1.1 Fixed factors

Current CT scanners generate images with isotropic voxel sizes as small as $0.4mm^3$. Importantly, the detector thickness of the scanner determines the z-axis "in-plane" resolution which varies between manufacturers from 0.4 to 0.7mm (Nicol & Padley, 2007a). As a result of this limitation CTCA can currently only distinguish stenoses to within 30% accuracy, compared with 10% on invasive coronary angiography (ICA) with a spatial resolution of 0.1-0.2mm. The spatial resolution of MR is typically 1-1.5mm but high resolution black blood images may be as low as 0.6mm.

### 2.1.2 Variable factors

In CT and MR the attenuation or signal values within each voxel are averaged out before being displayed on a grey scale image. Slice thickness is also modifiable; the thicker the slice, the greater the volume averaged and therefore the lower the spatial resolution. The trade-off with higher spatial resolution is increased noise. In both CCT and CMR spatial resolution can be improved by reducing the field-of-view, akin to zooming into an image. In CT coronary angiography, thin-cuts are obtained with the field of view reduced to just larger than the cardiac boundaries (Fig. 2).

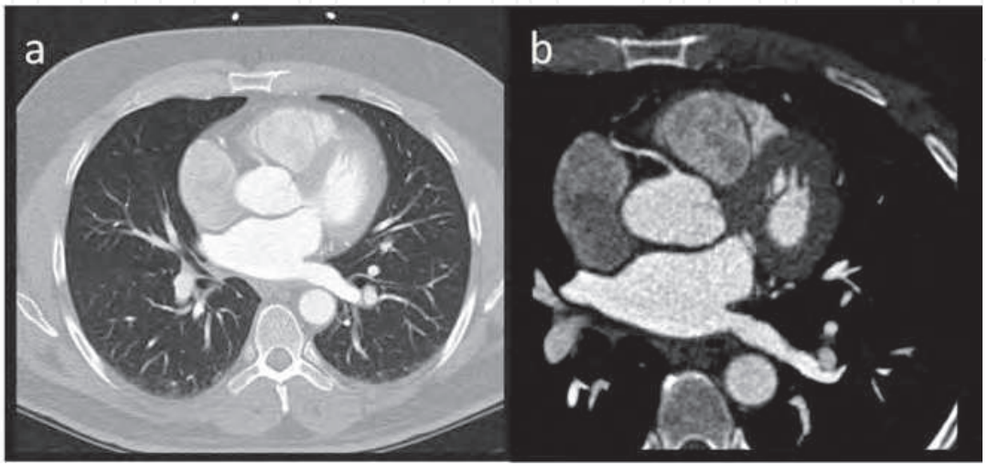



Fig. 2. The acquired scan is reconstructed to give a wide field-of-view (FOV) to include the lungs (a) and a smaller FOV to increase spatial resolution of cardiac structures (b).

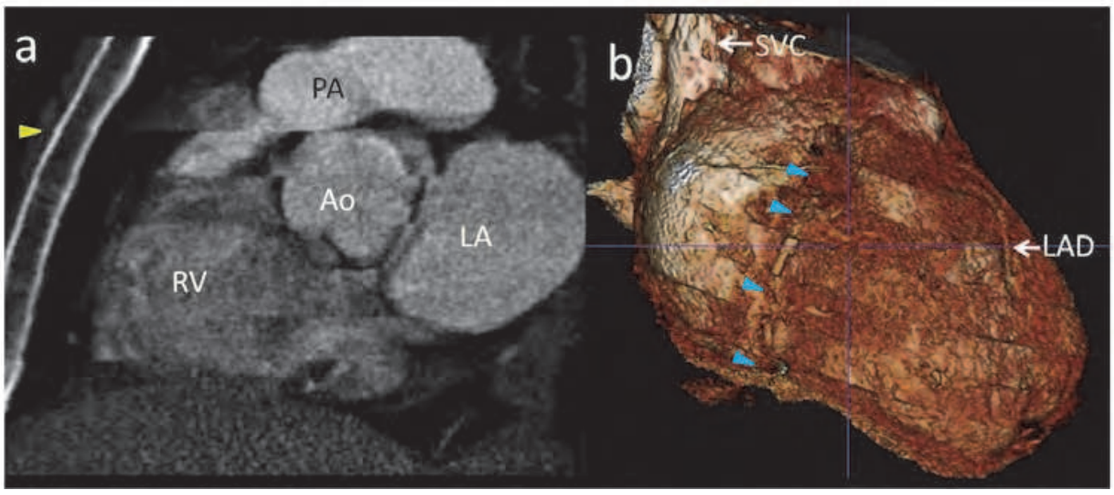



Fig. 3. Both cardiac and respiratory motion can lead to step artefact. These appear as horizontal lines on the sagittal dataset (panel a) and missing sections of the right coronary artery (blue arrowheads) on the volume rendered reconstruction (panel b). Respiratory rather than cardiac motion artefact can be distinguished by the involvement of the sternum (yellow arrowhead) in the former (panel a). (RV=Right Ventricle; Ao=Aorta; PA=Pulmonary Artery; LA=Left Atrium; SVC=Superior Vena Cava; LAD=Left Anterior Descending artery.)

Motion artefact impairs spatial resolution in both CCT and CMR. A well-prepared and co-operative patient who is able to comply with the breathing instructions will reduce the chance of step artefact (in CCT) (Fig. 3) and blurring (in CMR) due to respiration or movement. Reducing the heart rate reduces cardiac motion by increasing the diastolic phase during which coronary arteries move least. Arrhythmias, especially if irregular, may make prospectively gated studies impossible.

### 2.2 Temporal resolution

Cardiac motion artefact can also be reduced by acquiring images faster. In CCT this is achieved by increasing the speed of rotation of the gantry and the pitch of the table. This is similar to selecting a faster shutter speed on a camera and enables fast-moving structures such as coronary arteries to be captured with minimal blurring. Standard single source scanners with temporal resolution of 165 to 250 ms require heart rates to be <65bpm for optimal coronary image quality, and pharmacological rate control, usually with β-blockers, is ubiquitous. Dual source CT scanners have reduced the temporal resolution in CCT to 75ms with each detector array requiring only a quarter scan of data. This has made acquisition of CTCA possible at almost any heart rate (Flohr et al., 2006); however image quality is still improved at lower heart rates.

The temporal resolution of CMR is typically 50ms. It is preset by the technician and is not constrained by MR hardware as with CT. However, tachycardia does adversely affect image quality and lower heart rates are more desirable as the scan time is reduced and more k space is filled during each cardiac cycle (Kato et al., 2010).

### 2.3 Contrast resolution

Contrast resolution is the ability to distinguish between objects of different attenuation or signal when they are next to each other. In CT the coronary arterial wall and lumen have similar attenuation values and administration of intravenous contrast is therefore required. Adequate and well-timed opacification enables differentiation of the vessel wall from the lumen. Various components of atherosclerotic plaque also have different densities and are able to be characterised. This is an advantage of CTCA when compared with the pure lumenography of invasive catheter angiography. Coronary calcium can be readily identified on an unenhanced CT scan. However lipid-rich soft plaque, that is more prone to rupture and vessel remodelling are not visible without contrast administration (Fig. 4).

In CMR, exogenous contrast agents are usually not required. In 2D black blood sequences, a dual inversion recovery prepulse is used to make the blood appear black with persisting signal within the walls of the coronary arteries, producing images with reasonable contrast. For bright blood sequences, prepulses make the blood appear bright with adjacent tissues including myocardium and fat appearing dark. The prepulses used include T2 preparation pulses and fat saturation techniques, pre-programmed into the CMR sequence.

### 2.4 Patient preparation

Patient preparation is probably the most vital part of ensuring diagnostically adequate studies in both CCT and CMR. The patient selection process should identify those who would benefit from CTCA or MRCA and those who would be suitable to have the scan. Attention should be paid to patient factors such as excessive body mass index, arrhythmias, potential inability to keep still or follow breathing instructions or claustrophobia. If present, alternative means of coronary assessment should be considered.

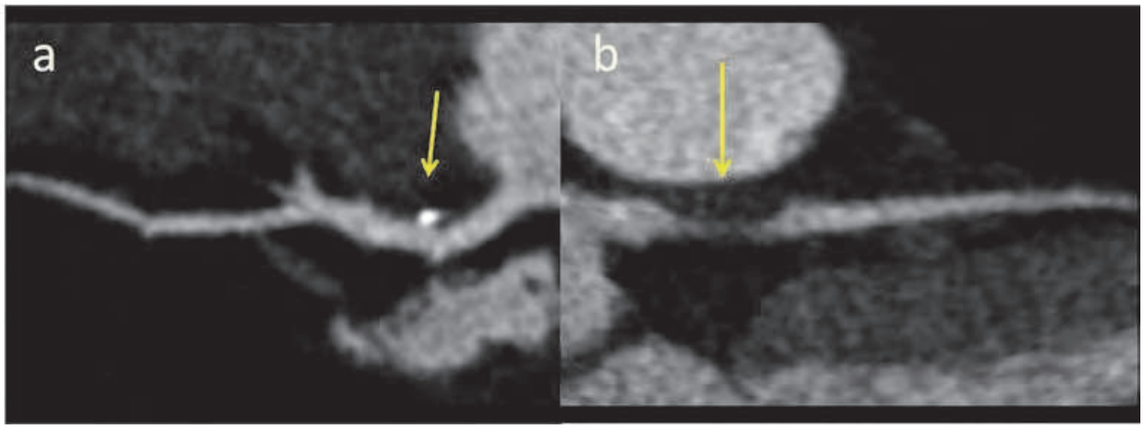



Fig. 4. Eccentric plaque (yellow arrows) can lead to positive remodelling (panel a) where the vessel expands to preserve lumen size, however continued plaque accumulation eventually leads to stenosis (panel b).

All patients referred for CCT or CMR should receive a patient information leaflet outlining the process of their scan. Patients are usually told to take their usual medications, including cardio-active medications, and to avoid consuming caffeine for twelve hours prior to the scan. On arrival, baseline observations including a heart rate and blood pressure should be taken. Patients should complete a questionnaire about allergies, relevant medical conditions and medications.

For CCT, contraindications to β-blockade and glyceryl trinitrate (GTN) are also ascertained. Intravenous access in the right antecubital fossa that allows rapid flow of contrast should be sited (18G or 20G cannula). The right side is used as it prevents high density contrast traversing the thorax and obscuring the cardiac structures through streak artefact (Nicol et al., 2008a).

For both CT and CMR, ECG electrodes are placed in the appropriate positions on the patient's chest to obtain a good amplitude R wave on the ECG trace. For CCT, where a low heart rate is critical, the heart rate is monitored and if just greater than 70 beats per minutes (bpm), breathing instructions alone may reduce the heart rate to < 65bpm. If the heart rate remains greater than 70bpm, negative chronotropic agents should be considered to reduce the heart rate.

For CCT the commonest drug used to reduce the heart rate is metoprolol. It is cheap, has a short half-life and is available in oral and intravenous (IV) forms, both of which are equally efficacious. Ideally, patients should be rate controlled prior to attendance at the CT department; however, if the heart rate remains high, IV metoprolol can be given immediately before acquisition. Ivabridine (Procoralan) can be used as an alternative to β-blockade in those with contra-indications. Sublingual GTN can be administered to promote vasodilatation of the coronary arteries and improve image quality but the patient should be warned about headaches as possible side effects (McParland et al., 2010).

### 2.5 ECG gating

Once the patient's heart rate is optimised, the appropriate CCT or CMR gating protocol is selected for the acquisition.

For CCT gating may be prospective or retrospective depending on the clinical scenario and information required. Cardiac motion is usually least in diastole, usually between 60-80% of

the R-R interval (Fig. 5). However, in patients with heart rates greater than 70bpm, imaging the heart in end-systole (35% of the R-R interval) may be better (Hoffmann et al., 2005).

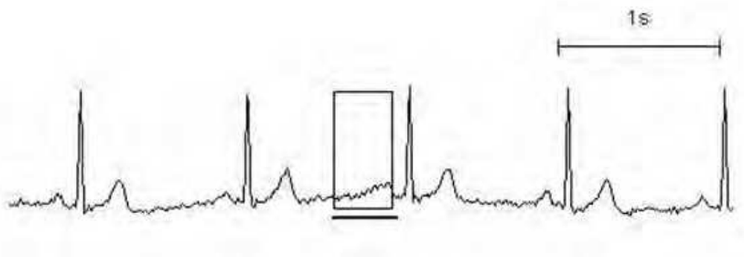



Fig. 5. Sample gated ECG where the heart is scanned during 60-80% of the cardiac cycle (diastole). This is when cardiac motion is likely to be at its minimum.

In order to minimise radiation dose, prospective gating (with variable temporal padding) is usually preferred if the heart rate is between 55 and 70bpm. However, if the heart rate cannot be optimised to less than 70bpm, or is irregular, a retrospectively gated study should be considered. Even with retrospective gating, newer scanning algorithms are able to limit the higher dose delivered to diastole (dose modulation). However, even with this, the retrospectively gated acquisition confers a higher radiation dose to the patient. However, as the heart is imaged throughout the whole cardiac cycle, additional information on cardiac output, ejection fraction and wall motion analysis can be obtained. With increasing experience, it may also be possible to perform diagnostically adequate prospectively gated studies in patients with certain arrhythmias as long as the heart rate variability is not too extreme. In CMR, prospectively triggered and gated scans are acquired.

## 3. Acquiring CTCA and MRCA

### 3.1 CTCA acquisition

The CT coronary angiogram is acquired in several steps – topogram, coronary calcium score, test bolus and contrast enhanced coronary angiogram.

#### 3.1.1 Coronary calcium scoring

The presence of calcium is a surrogate marker for atherosclerosis and an independent risk factor of future coronary risk. It is used as an adjunct to conventional risk stratification. To obtain a coronary calcium score, an un-enhanced scan is performed from the carina to just below the diaphragm. Good contrast resolution with CT enables quantification of the overall burden of disease. The usual scoring system is the Agatston calcium score (Agatston et al., 1990). Software used in coronary calcium scoring automatically detects any structure >130HU. The aggregate score of all detected calcium which lies within the coronary arterial tree is used to calculate the overall coronary calcium score.

#### 3.1.2 Contrast administration (test bolus and CTCA)

Intravenous contrast administration improves the contrast resolution of the coronary angiogram and is essential for lumenography. For CTCA a high iodine concentration (300-370 mg/ml) is required for appropriate opacification. Usually the contrast injection is given

as a timed bolus followed by a saline push to concentrate the dye in the left heart and aorta. The minimisation of contrast within the right heart and SVC reduces the likelihood of streak artefact interfering with the interpretation of the proximal right coronary artery.

The accuracy of the timing of the bolus may be improved by the use of a test bolus or bolus tracking to accurately determine the time taken to achieve peak concentration in the ascending aorta prior to full coronary assessment.

The test-bolus method determines the time to peak concentration of a small bolus of contrast in the aortic root. This time plus an additional 3-5 seconds (to allow adequate coronary opacification) is then used for the CTCA acquisition. The test bolus allows the patient to be aware of the common side effects of flushing and hopefully negates the potential heart rate response during the full CTCA contrast administration. Bolus tracking is similar to the test bolus but the scan and contrast injections are activated simultaneously. Once the contrast opacification in the region of interest reaches a predetermined threshold (usually 100-150HU), and following a preset delay (usually 5-8 second) to allow for breathing instructions or table movement, the full scan is started and the CTCA is acquired. Whilst the total radiation dose is slightly less, the timed bolus does not allow much room for error.

Whilst newer contrast media have an improved allergenic profile, any cardiac CT imaging service must be equipped to handle any potential contrast reactions. Patients with contrast media allergy may still undergo an un-enhanced coronary calcium score so that some information about their coronary risk profile can be obtained.

### 3.2 Post processing

CTCA images are best viewed on dedicated post-processing workstations. The table below shows the commonly used post-processing display protocols highlighting their advantages and drawbacks (Table 1).

| Protocol | Advantages | Disadvantages |
|---|---|---|
| Trans-axial or "raw" data scrolling (Fig. 6) | •Actual data set<br>•Accurate identification of stenoses<br>•Multiple "stacks" at different phases allow selection of optimal phase | •Need to be viewed in standard stacks, not good for communicating detail of vessels to non-radiologists<br>•No 3-D perspective |
| Multiplanar reformat (MPR) (Fig. 7) | •Interactive, semi-automated oblique or curved vessels plotted from axial, sagittal or coronal images to show vessel in its entirety<br>•360o rotations enables visualisation of eccentric and circumferential stenoses<br>•Accurate quantification of stenoses | •Image quality highly dependent on resolution and isotropy of original data volume set |
| Curved MPR (cMPR) (Fig. 8) | •Curved vessels can also be shown in complete linear conformation<br>•Advantages as for MPR | •Distortion of actual configuration of anatomical structures related to vessel of interest |
| Maximum intensity projection (MIP) (Fig. 9) | •Enhances differentiation between high attenuation structures such as enhanced vascular structures and lower attenuation structures such as soft tissue<br>•Allow more accurate quantification of "soft plaque" stenoses | •Loss of differentiation in regions of heavy calcification and stents due to over-projection of high density structures into the lumen<br>•No visualisation of the vessel wall |
| Volume rendered (Fig. 10) | •Intuitive, coloured images, allows assessment of whole 3D structures, good for communication of anatomy to non-radiologists<br>•Can "grow" coronary tree | •Not suitable for plaque assessment or accurate measurements<br>•Poor visualisation of calcium and stents |

Table 1. Comparison of commonly used post-processing display protocols. (Reproduced with permission from Nicol & Padley, 2007b).

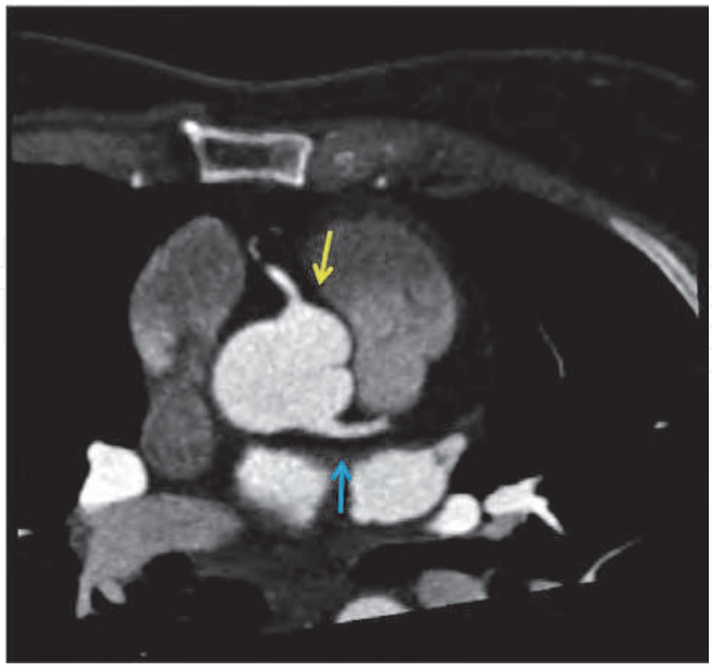


Fig. 6. Axial raw data through the heart showing the right and left coronary ostia (yellow and blue arrows respectively).

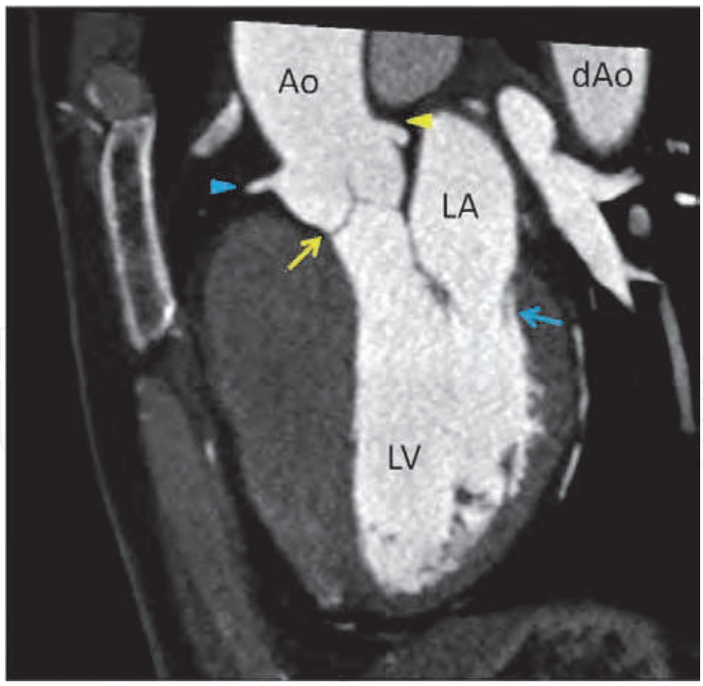



Fig. 7. Sagittal multiplanar reformat showing the closed aortic valve in profile (yellow arrow), open mitral valve (blue arrow) and right (blue arrowhead) and left (yellow arrowhead) coronary ostia. (LV=Left Ventricle; LA=Left Atrium;Ao=Aorta;dAo=descending Aorta).

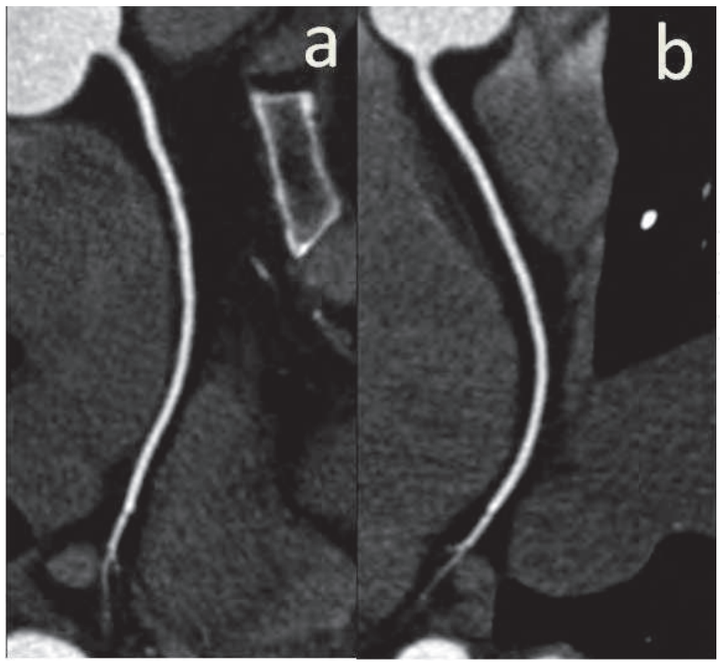



Fig. 8. Two curved multiplanar reformat images of the right coronary artery. These are obtained by rotating the image about a centreline through the artery.

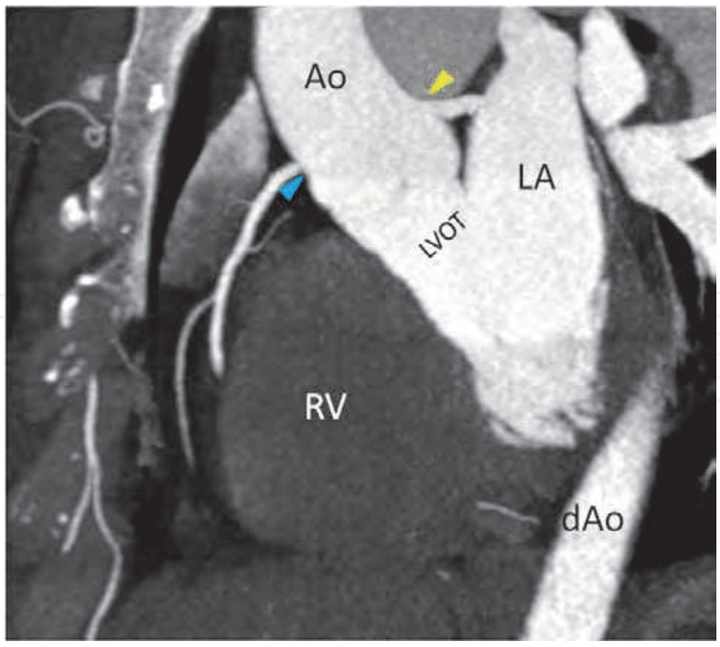



Fig. 9. Sagittal maximum intensity projection of showing the right (blue arrowhead) and left (yellow arrowhead) coronary ostia. (RV=Right Ventricle; Ao=Aorta;dAo=descending Aorta; LA=Left Atrium; LVOT=Left Ventricular Outflow Tract).

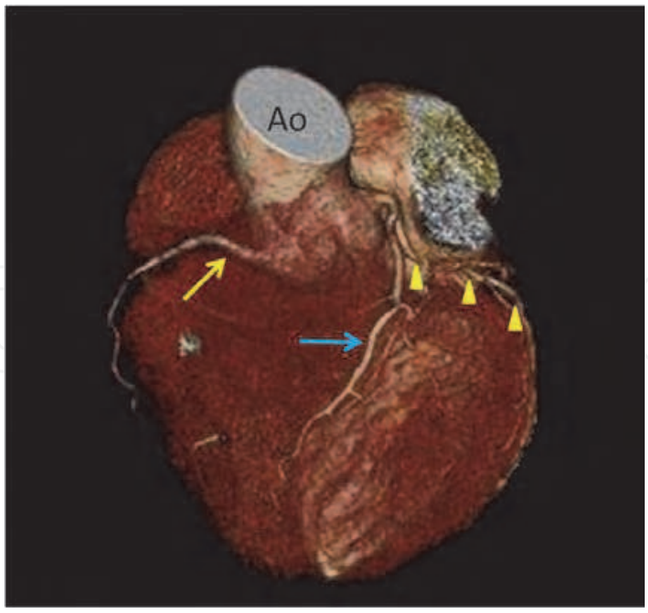



Fig. 10. Volume rendered image demonstrating a left anterior oblique view of the heart. The right coronary (yellow arrow), left anterior descending (blue arrow) and left circumflex (yellow arrowheads) arteries are clearly seen. (Ao=Aorta).

### 3.3 MRCA acquisition technique

There are two major hurdles to overcome when performing MRCA; respiratory and cardiac motion. Two methods are used to acquire MRCA images. These are breath-hold and free-breathing, coronary MRA. MRCA, as with CTCA, is further hampered by arrhythmias.

Breath-hold MRCA attempts to suppress respiratory motion by acquiring images in periods of apnoea. This technique allows both two-dimensional (2D) sequential images and subsequent shorter 3D imaging with first pass intravenous contrast. However, image quality is often suboptimal due to limited patient co-operation secondary to fatigue or inability to follow instruction adequately. Additionally breath holding is frequently associated with cranial drift of the diaphragm (of up to 1cm) (Danias et al., 1998), further limiting the final resolution of the images. These limitations may result in registration errors with apparent gaps in the coronary arteries that may be misinterpreted as signal voids from stenoses. As a result of these limitations free breathing navigator sequences are now most commonly used for MRCA.

Navigator sequences are used to correct for, and reduce the effects of, respiratory motion (Fig. 11). The position of the diaphragm is tracked and image data is only acquired at end expiration when respiratory motion is minimal or absent. Prospective ECG gating is used to correct for cardiac motion and data is only collected when coronary artery motion is known to be minimal. As with CTCA, this is usually mid-to-late diastole, however, at higher heart rates end-systole may be preferable. The disadvantages of this technique are that scan times are long with a full coronary dataset taking between 5 and 15 minutes to acquire (Sakuma et al., 2005, 2006). This is due to the fact that this technique is very inefficient with often less than 2% of the scan time being used to acquire data when there is neither coronary nor respiratory motion. The data acquisition is pre-programmed into the MRCA sequence,

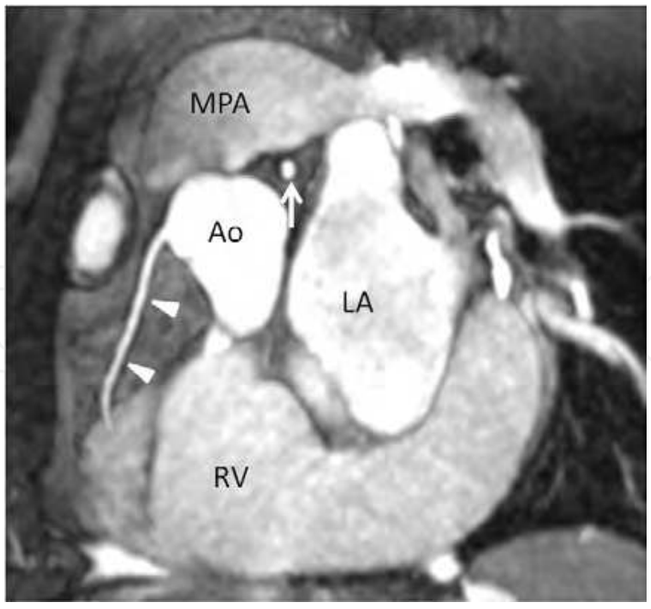



Fig. 11. Coronal view of the MRCA sequence showing the right coronary artery (arrowheads) as it passes through the AV groove. The left main stem is seen in cross-section (arrow) as it passes underneath the right pulmonary artery (RPA). (RV=right ventricle; MPA=main pulmonary artery; LA=left atrium).

although the user must define the time of least coronary motion at the time of acquisition. More recently 3D data acquisition during a single breath-hold using steady state free precession (SSFP) and parallel imaging has become possible (Deshpande et al., 2001) producing high resolution and high quality images with reduced scan times (Jahnke et al., 2005). Parallel imaging (with under sampling in two rather than one phase encoding direction) further reduces scan time but requires large coil arrays (Nehrke et al., 2006; Niendorf et al., 2006).

Newer self-navigated, free-breathing, whole heart MRCA techniques further improve image quality due to reduced respiratory and cardiac motion artifact. This technique uses a synchronous respiratory signal from the echoes acquired during imaging. The motion information is then retrospectively corrected, improving temporal resolution and producing stiller images (Stehning et al., 2005).

## 4. Clinical application of CTCA and MRCA

The significant technological improvements in CT imaging have brought CTCA into the forefront of coronary artery disease (CAD) assessment. With the improved temporal and spatial resolution, CTCA has become a viable alternative to invasive coronary angiography (ICA) in patients with low to intermediate likelihood of CAD (Schuijf et al., 2011). ICA however remains the most appropriate test in those with a high probability of severe CAD that may require intervention.

More broadly CCT can also be used to assess plaque morphology, and depending on the protocol selected, be used to assess cardiac function (wall motion and ejection fraction), cardiac chamber volumes, myocardial perfusion and be used to image the pericardium, cardiac valves, and pulmonary veins (Nicol et al., 2009). CCT is increasingly used to

examine acquired structural or congenital heart disease (Nicol et al., 2007), aberrant coronary vasculature, coronary artery bypass grafts (CABG) (Niemen et al., 2003) and intra-coronary stents (Gaspar et al., 2005).

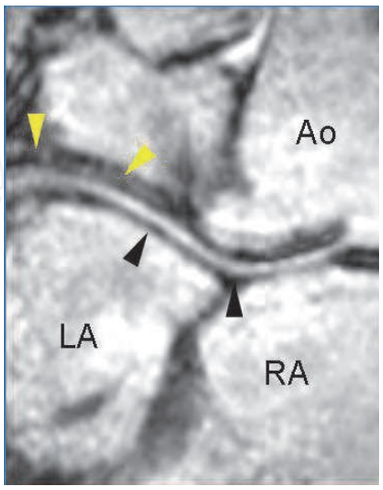



Fig. 12. Maximum intensity projection image from a navigator coronary MRA sequence demonstrating an aberrant circumflex artery (black arrowheads) arising from the right coronary artery passing between the aorta (Ao) and the right atrium (RA). Note also the resultant artefact (yellow arrowheads) due to cardiac motion. (LA=left atrium).

MRCA is most commonly used to investigate patients with suspected anomalous coronary arteries (Fig. 12) and fistulae, and in children and young adults with suspected coronary artery aneurysms such as in patients with Kawasaki's disease. It can potentially be used to assess graft patency in CABG; however the presence of surgical clips may limit graft visualisation. In patients with poor renal function, MRCA can be used to assess the patency of proximal coronary arteries in patients undergoing major cardiac surgery, such as valve replacement, as no contrast agent is used.

### 4.1 CT and MR coronary angiography

Unlike ICA that provides a "lumenogram", a good quality CTCA can demonstrate both the lumen and the wall. The real strength of CTCA is its negative predictive value (usually over 99% *cf*. ICA), effectively ruling out coronary artery disease in those with a normal study (Budoff et al., 2008; Meijboom et al., 2008). The positive predictive value of CTCA is less favourable due its comparatively limited spatial resolution. The diagnostic accuracy of CTCA is further impaired by the presence of heavy coronary calcification, which may lead to the overestimation of stenoses. All coronary stenoses should be viewed from multiple angles and appropriate window settings to reduce "blooming" artefact from calcium. If contrast is seen passing alongside a calcified lesion in any plane, then the stenosis is unlikely to be more than 50% on ICA. CTCA is as effective in determining soft plaque burden as intravascular ultrasound (IVUS) (Leber et al., 2006). Clinically this is important due to the higher prevalence of soft plaque in those patients with acute coronary syndromes than those who have stable angina (Korosoglou et al., 2010; Motoyama et al., 2007). An algorithm for the investigation of symptomatic patients based on their pre-test probability is suggested (Fig. 13).

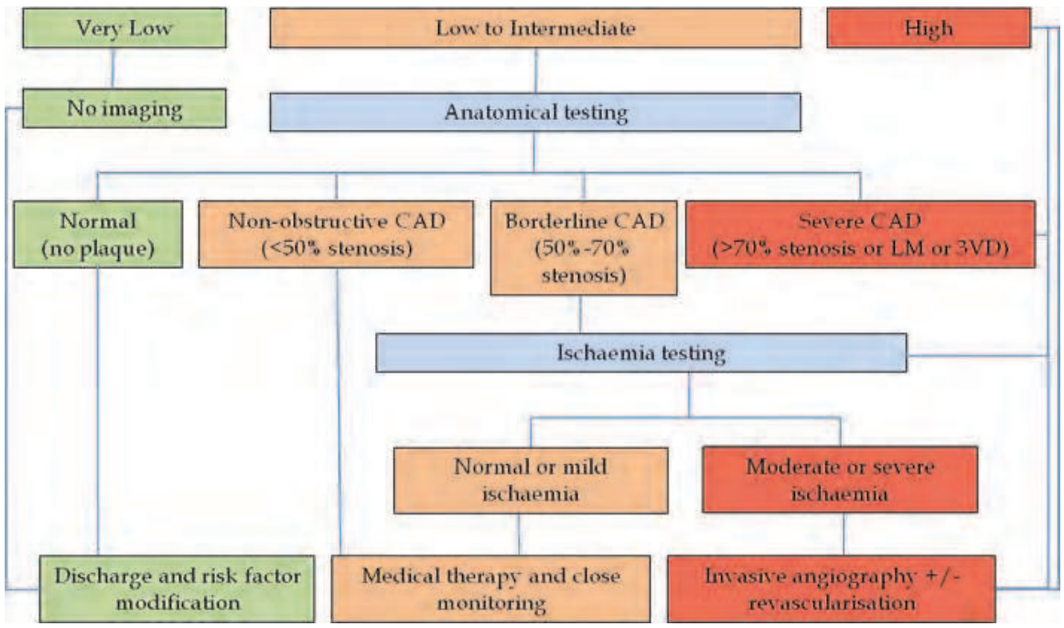



Fig. 13. Potential algorithm for sequential imaging of anatomy and function for diagnosis and management of coronary artery disease (CAD) based on pre-test probability in symptomatic patients. A low to intermediate pre-test probability favours initial evaluation of the presence or absence of obstructive stenosis, since the prevalence of obstructive CAD will be low. As a consequence only a few patients will have abnormalities that may require further testing and revascularisation. (LM = left main coronary artery; 3VD = triple vessel disease.) Adapted with permission from Schuijf JD et al., 2011).

Like CTCA, MRCA is able to demonstrate both the lumen and vessel wall. However CMR studies routinely provide additional cardiac anatomy and functional information. Compared with CTCA the speed of acquisition and spatial resolution of MRCA has so far limited its use clinically. There are important technical differences between CTCA and MRCA; in CTCA the right coronary artery is often the most difficult vessel to image due to movement artifact, especially in prospectively acquired imaging, but in MRCA the left circumflex artery is relatively difficult to image due to its distance from the receiver coil and its proximity to the great cardiac vein (Danias et al., 1999). As with CTCA, multiple studies have assessed the accuracy of MRCA for the detection of significant CAD. In essence MRCA, like CTCA, has a high negative predictive value but variable specificity and positive predictive value (Danias et al., 2004; Kato et al., 2010; Kim et al., 2001; Schuetz et al., 2010). MRCA is particularly useful in left main coronary and three vessel disease assessment (Kato et al., 2010; Kim et al., 2001) (Fig. 14) but overall 1.5T CMRA is comparable with 16 MDCT when assessing the entire coronary tree (Kefer et al., 2005).

Wall thickness and plaque characterisation are significant areas of research in both CTCA and MRCA as plaque rupture and myocardial infarction can occur in the absence of significant luminal narrowing. In MRCA, T1 weighted 2D and 3D black blood imaging can detect atherosclerotic plaque and determine wall thickness and thus positive remodelling (Fayad et al., 2000; Kim et al., 2002), whilst CTCA studies have demonstrated that the presence of positive remodelling and "spotty" plaque morphology (a predominantly soft plaque with some areas of calcification within it) are strongly associated with subsequent

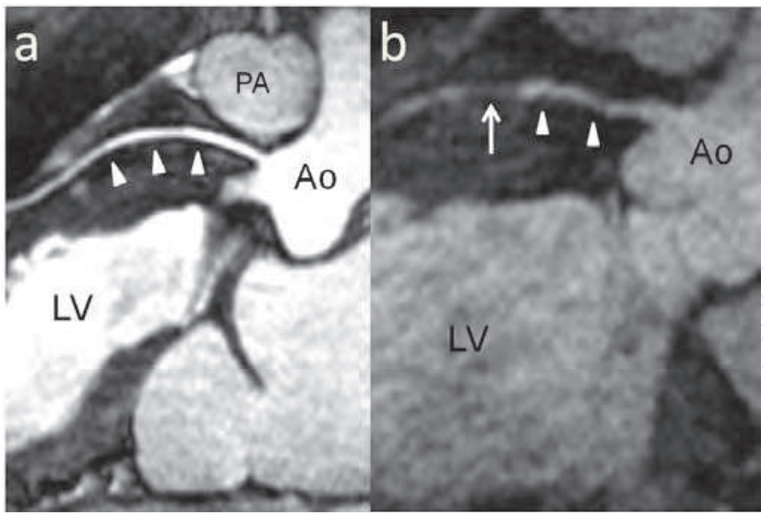



Fig. 14. Maximum intensity projection image (a) from a navigator coronary MRA sequence demonstrating a normal calibre left anterior descending artery (arrowheads). The second image (b) shows non-occlusive, non-calcified plaque (arrow) in the mid left anterior descending artery (arrowheads) on this coronary MRA. (Ao=aorta; LV=left ventricle; PA=pulmonary artery).

acute coronary syndrome (Motoyama et al., 2007). MRCA has been used to demonstrate positive remodelling in diabetic patients with nephropathy compared with those without (Kim et al., 2007) and recent evidence demonstrates that high signal on T1 weighted images seen in plaques in the walls of coronary arteries is associated with positive remodelling. This suggests MRCA may also be useful for investigating complex plaques non-invasively (Kawasaki et al., 2009). Late contrast enhancement of the coronary arterial wall in MRCA has been seen in areas of calcific plaque and significant stenotic lesions following recent infarcts (Yeon et al., 2007; Ibrahim et al., 2009) and it has been proposed that late contrast enhancement may be useful in visualisation of inflammatory activity in atherosclerosis associated with acute coronary syndrome. For early CAD assessment, recent studies have shown that MRCA can demonstrate endothelial loss of normal vasomotor tone prior to the development of any vascular remodelling (Hays et al., 2010).

### 4.2 Coronary stent assessment

Clinically all stents are susceptible to varying degrees of neo-intimal hyperplasia, in-stent re-stenosis and complete occlusion. The metal in the stents make them easily visible on CT (Fig. 15) however CTCA analysis of stents must be done cautiously due to "blooming" artefacts (Nicol & Padley, 2007b). Blooming is worse with bare metal stents than drug eluting stents but CTCA has been shown to be clinically reliable for stents >3mm in diameter and is clinically useful in the assessment of left main stem stents (Pugliese et al., 2008). Stents of smaller calibre are less easily assessed and caution is advised when attempting to determine the severity of stenoses.

### 4.3 Coronary artery bypass graft assessment

The inherent larger calibre of vessel grafts, relative immobility and lack of calcification, make them ideally suited to CTCA analysis (Fig. 16). Indeed, the sensitivity and specificity

of CTCA in graft patency analysis has been shown to be 95-100% and 94-100% respectively (Nieman et al., 2003).

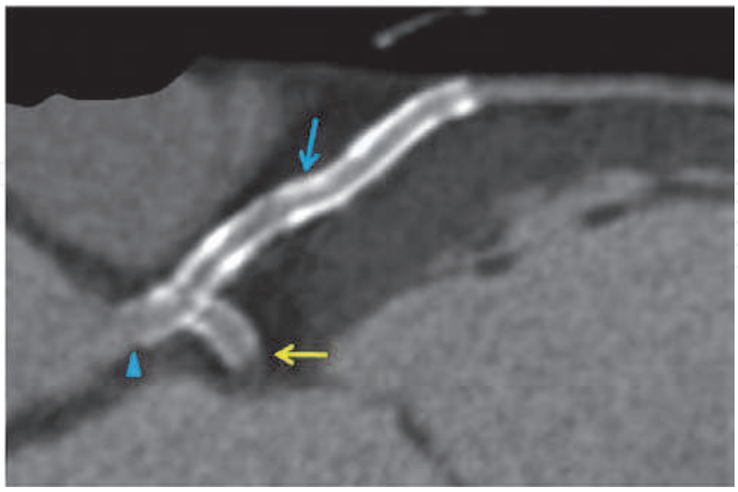


Fig. 15. Curved planar reformat of a metal stent extending from the left main stem (blue arrowhead) into left anterior descending (blue arrow) and left circumflex (yellow arrow) arteries.

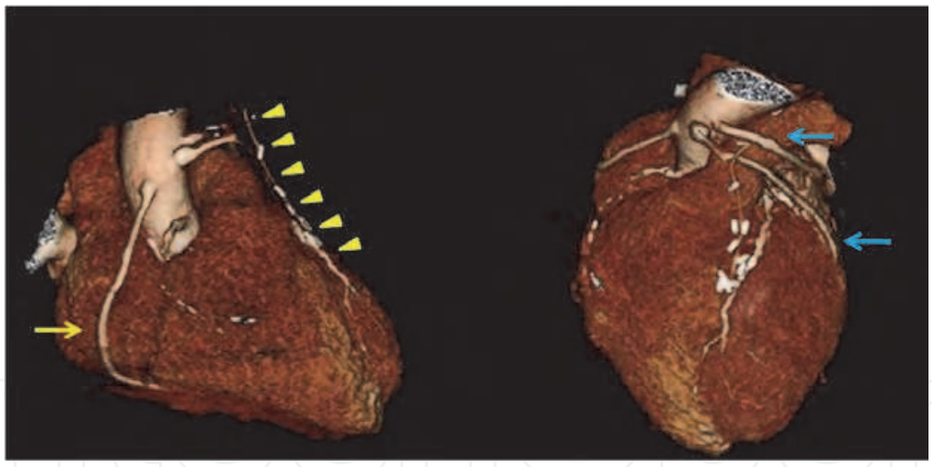


Fig. 16. Volume-rendered images demonstrating quadruple coronary artery bypass grafts. There are a vein graft to the right coronary artery (yellow arrow), two vein grafts supplying the acute marginal and lateral marginal branches of the LCx (blue arrows) and a left internal mammary artery graft supplying the left anterior descending artery (arrowheads).

However, complete examination of grafts and their patency should include assessment of their run-off which may be limited with CT. Limitations of CTCA include blooming artefact from surgical clips which can particularly affect distal LIMA anastomosis assessment. CABG patients often have significant and heavy calcification, which can also cause blooming artefact on CTCA. MRCA can also be used to assess CABG but again surgical clips may hinder full assessment.

### 4.4 Functional information

Whilst CMR remains the gold-standard for cardiac functional analysis, retrospectively gated CCT studies allow assessment of global and regional left ventricular function with good correlation with both CMR and transthoracic echocardiography (Nicol et al., 2008b). It is important to be aware of limitations of CCT however when assessing both global and regional wall motion abnormalities especially if not reconstructing 100% of the cardiac cycle. Whilst end-systole and end-diastole usually fall at around 35% and 65% respectively there is significant inter-patient variation and values from the analysis may not reflect that of CMR or echocardiography that routinely utilise the whole cardiac cycle. Importantly, when assessing functional CT data regional wall motion abnormalities in the absence of impaired systolic wall thickening should also be treated with caution as they may be artefactual (Nicol et al., 2008).

## 5. Clinical application of CTCA and MRCA in congenital and structural heart disease assessment

Both CCT and CMR are able to demonstrate complex anatomy in congenital cardiac disease. CMR remains the gold standard for adult congenital heart disease assessment but the increasing availability, speed of acquisition and superior spatial resolution of CCT makes it a viable alternative in many clinical situations (Nicol et al., 2007). CMR is generally contraindicated in patients with pacemaker and implanted defibrillator devices.

Unlike CMR, that offers complete cardiothoracic visualisation, CCT is only able to demonstrate both the coronary anatomy and the pulmonary arterial trunk with extended injection protocols that increase right heart and pulmonary opacification in addition to the coronary anatomy (Nicol et al., 2009). CTCA is the gold standard for the full delineation of aberrant coronary anatomy, however MRCA is, in most patients, adequate for delineation of the clinically important coronary ostia and using dedicated sequences can also sometimes produce diagnostic images of the entire coronary tree. As a general rule, MRCA should be considered first line if radiation exposure is likely to be higher than acceptable, i.e. in children or young females, and MRCA should certainly be considered in those requiring regular follow up such as Kawasaki's disease.

Increasingly CCT is used for acquired structural heart disease and assessment of valve disease using planimetry and assessment of valve function on cine images acquired in retrospectively gated studies is gaining clinical acceptance (Chheda et al., 2010). It is important to remember however that CCT is unable to assess flow and is therefore inferior to both CMR and echocardiography for the assessment of valve gradients.

Combined cardiac and non-cardiac angiography is now used in the assessment of trans-catheter aortic valve implantation (TAVI). Assessment of the aortic root size, aortic pathology (plaque burden, calcification, vessel tortuosity), access routes (ilio-femoral and subclavian arteries), coronary arteries and valve calcification can all be assessed using CT angiography (Ewe et al., 2011) (Fig. 17).

## 6. Future developments in CT and MR

### 6.1 CCT imaging

There have been significant advances in CT scanner technology over the last decade with the advent of increasing numbers of detectors (up to 320) allowing whole heart coverage

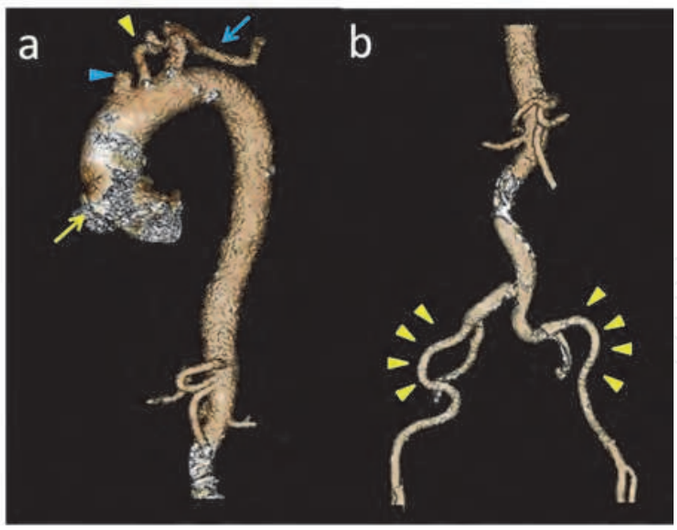



Fig. 17. Volume rendered images of the aorta obtained as part of the TAVI assessment protocol. The level of the aortic root (yellow arrow), right subclavian artery origin (blue arrowhead), right carotid artery (yellow arrow head) and left brachiocephalic artery (blue arrow) are shown in (a). The tortuosity of the iliofemoral arteries (yellow arrowheads) demonstrated in (b), will help with surgical planning.

without table feed, and fast pitch dual source CT allowing a full cardiac acquisition in a fraction of a second with radiation doses routinely <1mSv for a CTCA.
Future technological advances are likely to remain focused on rapid acquisition of cardiac data at low ionizing radiation doses. This may be achieved using a variety of techniques such as multi-source, multi-energy CT or inverse geometry CT.

### 6.2 Multi-source, multi-energy CT

By increasing the number of X-ray sources it may be possible to further reduce the temporal resolution by two-thirds with the addition of a third source (58ms) or three-quarters with a fourth (41ms), however the weight of each additional X-ray source may reduce the overall gantry rotation time negating any additional benefit. The use of air bearing systems may allow this but the ability to overcome the effects of high centrifugal forces remains a significant challenge.
The major advantage of dual source CT (DSCT) technology is the ability to acquire a complete dataset using one-quarter of a gantry rotation time, thereby reducing the temporal resolution by half. The second advantage of dual headed CT is the ability to acquire the dataset at differing energies (Dual energy CT (DECT)). It is also possible to perform DECT on single headed scanners by rapidly alternating kV from a single tube. Either technique fundamentally alters the penetration of the X-ray beam and therefore the attenuation by tissues. By subtracting one dataset from the other it is possible to, for example to artificially "remove" calcium or contrast, potentially spelling the end for non-enhanced CT preceding contrast studies. It may also be used to assess myocardial densities at different energies, paving the way for potential tissue characterization in infarct or ischaemic myocardium. DECT subtraction techniques are currently limited to large calibre vessels such as the aorta as the resolution of the current generation of CT scanners is not yet sufficient to apply this to the coronary arteries.

### 6.3 Inverse Geometry CT (IGCT)

IGCT is a novel system under investigation that employs a large array of X-ray sources opposite a smaller detector array (Fig. 18). It is anticipated to be able to image a thick volume in a single gantry rotation with isotropic resolution. The ability to image a volume is primarily determined by the size of the X-ray source array, in much the same way that it is determined by the size of the detector array in a conventional CT system. As well as demonstrating low wasted radiation (Mazin et al., 2007) (and therefore a much smaller radiation requirement), this technique also has the potential to maximise gantry rotation time further reducing spatial resolution.

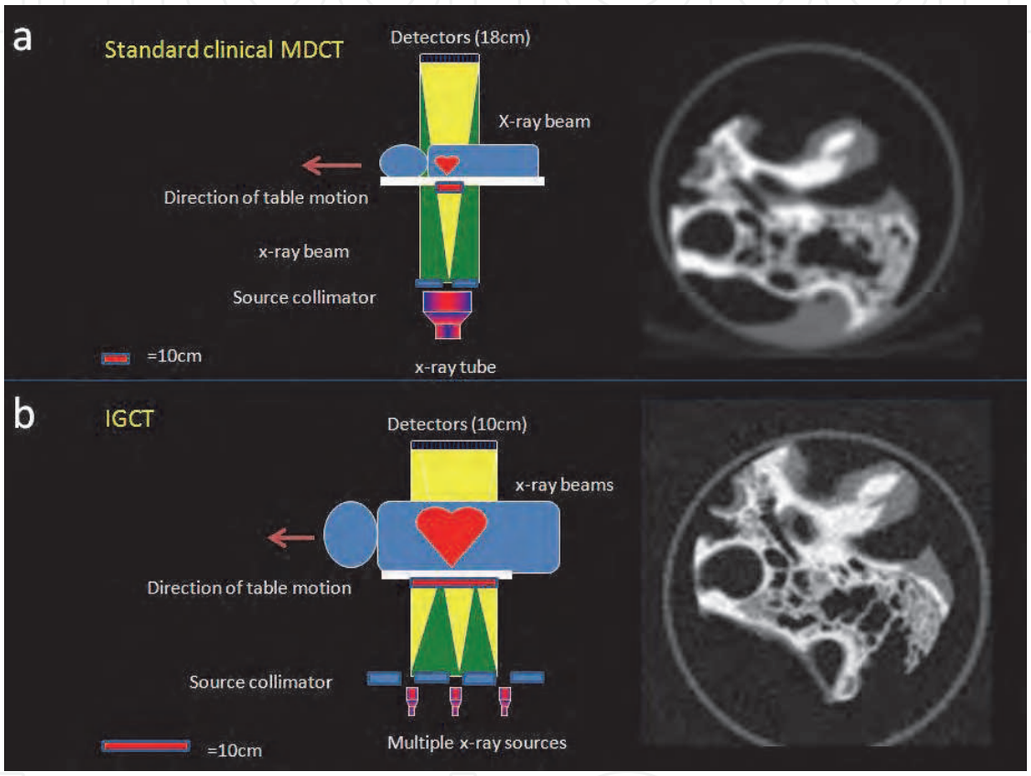



Fig. 18. Standard MDCT (a) requires an 18cm detector array when scanning a 10cm region of interest (due to cone beam) introducing artefacts at beam edges. Inverse Geometry CT (IGCT) (b) uses multiple x-ray sources and only requires a 10cm detector array for a 10cm region of interest, reducing detector size and weight, reducing cone beam artefact and producing greater signal to noise ratios for reduced radiation exposure.

Future advances in material technology will also advance CT imaging with flat panel technology already under investigation. The use of strong light weight materials may also overcome some of the mechanical limitations that prevent faster gantry rotation times today and may improve spatial and temporal resolution to nearer that of interventional coronary angiography.

### 6.4 3T CMR imaging

At 3T, there is improved signal to noise ratio (SNR) as SNR is proportional to the field strength of the static magnetic field (Singerman et al., 1997). 3T results in better spatial and

temporal resolution and shorter scanning time. There is a doubling of SNR and a 4-fold reduction in scanning time using 3T parallel imaging and spatial harmonics compared with 1.5T. Additionally, at higher field strengths the prolongation of the T1 values make spin labelling techniques more attractive. However triggering is more problematic at higher field strengths (3T and 7T) as the enhanced magneto-hydrodynamic effect produces an artifactual voltage that is overlaid on the T wave of the ECG. This can result in triggering off the T wave (rather than the R wave) making it difficult to reliably identify the time of least coronary motion. Using sophisticated R wave detection algorithms this problem can be overcome.

MRCA at 3T has been performed (Stuber et al., 2002) however although the contrast to noise ratio is improved, there is no overall improvement in image quality or diagnostic accuracy (25). 3T MRCA has been shown to have high sensitivity and specificity for the detection of significant (>50%) coronary stenoses (Yang et al., 2009), possibly even being comparable to 64 MDCT (Hamdan et al., 2011) when using contrast-enhanced methods that rely on double dose infusion of contrast media. This is required as gradient-echo sequences are used instead of SSFP sequences due to the need to overcome magnetic field inhomogeneity and radiofrequency energy deposition at high field strengths (Bi et al., 2007; Liu et al., 2008). It is hoped that the use of sophisticated shimming algorithms and adiabetic T2 preparations will further improve acquisition at 3T (Nezafat et al., 2006; Schär et al., 2004) in the future.

## 7. Future application of CTCA and MRCA

Both CCT and CMR continue to develop rapidly. The applications for CTCA continue to expand and with the development of myocardial perfusion and scar imaging the ability to look at the coronary lumen and vessel wall and gain functional information about both the blood flow and myocardial function will see this field continue to expand.

The recent UK NICE guidelines include CTCA within their recommendations for patients with chest pain (NICE, 2010) and the ever growing demand for rapid exclusion or confirmation of coronary artery disease are likely to see CTCA become a far more ubiquitous tool used in almost all hospitals.

As radiation doses continue to fall and as CTCA research produces outcome and cost effectiveness data, the role and utilisation of this rapidly evolving technology is likely to increase further. The combination of newer technology has raised the possibility of assessing flow; indeed venous and arterial phases of cerebral flow can already be imaged using CT and this opens up many possibilities for potential cardiac flow assessment in the future.

In MRCA, the greater availability of more powerful magnets, increased number of receiver coils and more sophisticated algorithms, may reduce imaging time. MRCA may become routine in the early detection of coronary artery disease at the positive remodelling stage or even earlier. Plaques at risk of rupture may be identified early and intervention undertaken before myocardial damage occurs.

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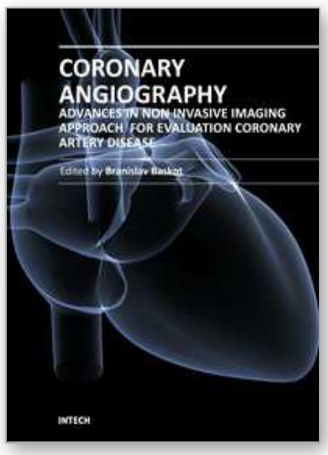
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**Coronary Angiography - Advances in Noninvasive Imaging Approach for Evaluation of Coronary Artery Disease**

Edited by Prof. Baskot Branislav

ISBN 978-953-307-675-1
Hard cover, 414 pages
**Publisher** InTech
**Published online** 15, September, 2011
**Published in print edition** September, 2011

In the intervening 10 years tremendous advances in the field of cardiac computed tomography have occurred. We now can legitimately claim that computed tomography angiography (CTA) of the coronary arteries is available. In the evaluation of patients with suspected coronary artery disease (CAD), many guidelines today consider CTA an alternative to stress testing. The use of CTA in primary prevention patients is more controversial in considering diagnostic test interpretation in populations with a low prevalence to disease. However the nuclear technique most frequently used by cardiologists is myocardial perfusion imaging (MPI). The combination of a nuclear camera with CTA allows for the attainment of coronary anatomic, cardiac function and MPI from one piece of equipment. PET/SPECT cameras can now assess perfusion, function, and metabolism. Assessing cardiac viability is now fairly routine with these enhancements to cardiac imaging. This issue is full of important information that every cardiologist needs to now.

**How to reference**

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Mohanaluxmi Sriharan, Paula McParland, Stephen Harden and Edward Nicol (2011). Non-Invasive Coronary Angiography, Coronary Angiography - Advances in Noninvasive Imaging Approach for Evaluation of Coronary Artery Disease, Prof. Baskot Branislav (Ed.), ISBN: 978-953-307-675-1, InTech, Available from: http://www.intechopen.com/books/coronary-angiography-advances-in-noninvasive-imaging-approach-for-evaluation-of-coronary-artery-disease/non-invasive-coronary-angiography

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